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Fatigue analysis of HHI SkyBench™ 19000 TEU ultra large container ship with springing effect included

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Abstract. The importance of analyzing hydroelastic vibratory responses (springing and whipping) of ship hull structure and their effects on structural fatigue damage is increasing in line with building of larger and consequently more flexible ships. On the other hand, reliable structural design of such ships cannot be achieved by applying only rule based formulae, and therefore direct calculation approach is required. This is particularly emphasized in case of ultra large container ships (ULCS). In this paper, preliminary results of hydroelastic analysis of a newly designed HHI SkyBench™ container ship, related to the fatigue assessment of several structural details, are presented. The analysis was performed by general hydro-structure tool HOMER, where 3D FEM model for the structure and 3D potential flow code for fluid modelling, respectively, is used. An outline of the numerical procedure based on the modal approach is given and features of new HHI SkyBench™ container ship design are described. The result section includes fatigue life assessment of selected fine-mesh structural details with springing effect included, obtained by the top-down approach.

Key words: *hydroelasticity; springing; potential flow; finite element method; SkyBench™ container ship*

1. Introduction

Specific characteristic of Ultra Large Container Ships (ULCS), compared to the other types of ships, is that they are more likely to experience the hydroelastic type of structural response called springing and whipping [1,2]. That is mainly caused by their large dimensions, relatively high operational speed and large bow flare. The evaluation of the hydroelastic response and its inclusion into the overall design procedure, is significantly more complex problem than the calculation of quasi-static

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structural response [2]. The Rules of classification societies are not directly applicable to ULCSs, and therefore direct calculations are necessary for their safe and rational design. In this context some classification societies have developed guidelines for inclusion of hydroleastic effects within the direct calculation approach. Also, for the purpose there are several hydro-structure software available around the world, mainly relying on the same theoretical assumptions, but having incorporated different numerical procedures. Such tools are mostly based on the application of the 3D potential flow theoretical models for fluid flow coupled with the 3DFEM structural models.

In this paper, preliminary results of hydroelastic analysis of new SkyBench^{TM} container ship, designed by Hyundai Heavy Industries (HHI) are presented. Compared with conventional design SkyBench^{TM} CS has an additional hatch opening, which could make the vessel relatively vulnerable to warping deformation. Since both the ship having L_{OA}=400 m and SkyBench^{TM} concept are out of the range of Rule-based design, a series of computation is being performed to check ship's compatibility with additional class notation WhiSp [3]. Nowadays, maximized space utilization in container carriers for securing maximized cargo capacity in the restricted dimension is one of the design keys since container carriers load boxes not only inside cargo holds but also on deck. SkyBench^{TM} is a container carrier which adopts mobile concept at accommodation. This new design utilizes unused spaces which are surrounding accommodation in the container carriers with 2-island type. SkyBench^{TM} gives not only extended cargo capacity but different vibration characteristics compared with the traditional design. The analysis is being conducted according to the Bureau Veritas (BV) Rule Note 583 [3] and the results presented here are only the ones related to the fatigue assessment of several structural details taking into account the springing effect. A general hydro-structure tool HOMER [4,5], developed by BV, where 3D FEM model for the structure and 3D potential flow code for fluid modelling, respectively, is used.

The paper is structured into 5 sections. In the second one, an outline of the numerical procedure based on the modal approach is given, and stress concentration calculation by HOMER is briefly described. In the third section the basic features of HHI SkyBench^{TM} concept as well as used calculation models and setup are presented. Beside fatigue life of selected fine-mesh structural details, obtained by the top-down approach, the fourth section includes some specific results inherent to unique balancing procedure available within the used software. Quasi-static and hydroelastic contributions are clearly separated in order to assess the relative influence of hydroelasticity. Finally, preliminary conclusions are drawn and guidelines for further investigation are given.

2. Procedure

Linear hydroelastic analysis performed here is based on the mode superposition method [6]. Within the modal approach, total displacement of a ship is expressed through a series of modal displacements:

$$\boldsymbol{H}(x,t)=\sum_{i=1}^{N}\xi_i(t)\boldsymbol{h}^i(x), \tag{1}$$

where $\boldsymbol{H}(x,t)$ represents total displacement of one point, $\boldsymbol{h}^{\boldsymbol{i}}(x)$ is modal displacement (mode shape), $\xi_i(\mathrm{t})$ is modal amplitude, and N represents the total number of modes [5]. Generally, the procedure is very similar to rigid body analysis described in [2] except that the number of degrees of freedom is extended from 6 to 6 plus a certain number of elastic modes. The used modal approach implies the definition of supplementary radiation potentials with the following body boundary condition:

$$\frac{\partial\varphi_{Rj}}{\partial n}=\boldsymbol{h}^j\boldsymbol{n}, \tag{2}$$

where $\boldsymbol{n}$ is unit normal vector. After solving the different boundary value problems for the potentials, the corresponding forces are calculated and the motion equation is written

$$\left\{-\omega^2\left(\mathbf{m}+\mathbf{A}\right)-i\omega(\mathbf{B}+\mathbf{b})+(\mathbf{k}+\mathbf{C})\right\}\boldsymbol{\xi}=\mathbf{F}^{DI}, \tag{3}$$

where $\mathbf{m}$ is the modal structural mass, $\mathbf{b}$ is the structural damping, $\mathbf{k}$ is the structural stiffness, $\mathbf{A}$ is the hydrodynamic added mass, $\mathbf{B}$ is the hydrodynamic damping, $\mathbf{C}$ is the hydrostatic restoring stiffness, and $\mathbf{F}^{DI}$ is the modal hydrodynamic excitation vector.

Once the modal amplitudes have been calculated the total stresses can be obtained, at least theoretically, by summing the individual modal contributions and one can formally write, [2]:

$$\Sigma(x,\omega)=\sum_{i=1}^{N}\xi_i(\omega)\sigma^i(x), \tag{4}$$

where $\Sigma(x,\omega)$ is the total stress and $\sigma^i(x)$ is the spatial distribution of modal stresses.

In order to practically take into account hydroelastic effects on the structural response, dynamic analysis computational scheme is applied, starting with modal analysis in dry condition, Figure 1, [3]. Once the dry modes are obtained, the modal displacements are transferred from the structural model to the hydrodynamic one, and corresponding hydrodynamic problem is formulated. After that, fully coupled dynamic equation is solved, giving the modal amplitudes.

In order to cover all types of hydro-structural interactions inherent ships and offshore structures described in [5], the numerical software HOMER is developed in Bureau Veritas Research Department for the direct transfer of the seakeeping loads from the general seakeeping code to a structural FE model, Figure 2, [4,5]. HOMER modules presented in Figure 2 are intended to be used as follows: HMFEM – to compute mass and inertia properties of FE model. Run modal analysis, HMSWB – to analyse still water load case and perform balancing, HMHST – for running hydrodynamic pressures computations using the seakeeping code, HMMCN - solves mechanical problem, HMFEA – to run FE analysis on load cases, HMRAO - to create RAOs and HMTIME – to perform time-domain analysis.

Three main ideas introduced through HOMER software to obtain the perfect equilibrium of the structural model are the following, [5]:

1. Recalculation of the pressure at the structural points (instead of interpolation)
2. Separate transfer of the different pressure components, and calculation of the different hydrodynamic coefficients by integration over the structural FE mesh.
3. Solution of the motion equation using the above calculated hydrodynamic coefficients and inertia properties of the FE model. This point ensures the perfect equilibrium of the FE load case because of calculation of all the coefficients of the motion the FEM model.

Within the investigation presented in this paper, HOMER is used with Hydrostar [7] as the hydrodynamic solver, and NASTRAN [8] as the structural solver.

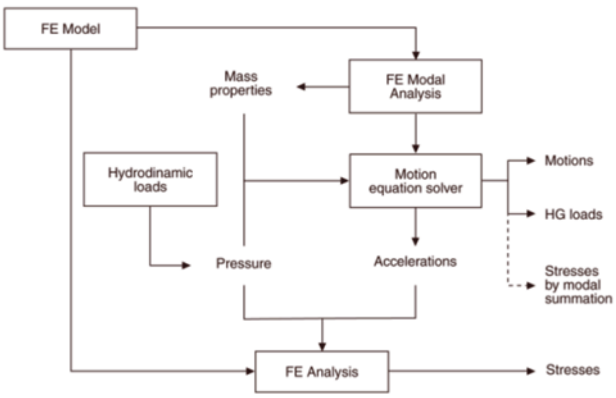


Figure 1. Dynamic analysis computational scheme [3].

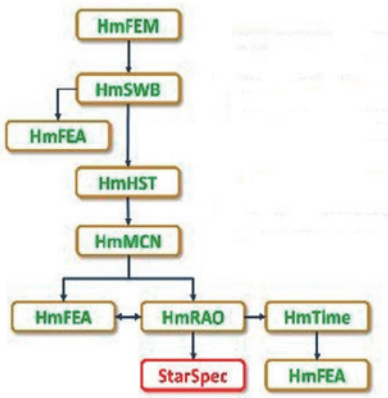


Figure 2. Flowchart of HOMER software [4].

Fatigue assessment of HHI SkyBench^{TM} CS structural details is performed according to the flowchart presented in Figure 3.

For the fatigue life calculation, very local stress concentrations at some particular structural details are needed, and generally they can be calculated by refining the global coarse mesh or using the so called top-down approach. The former approach seems to be impractical leading to excessive number of finite elements, and therefore here, the latter one is used, which implies solving the global coarse mesh FEM problem at first, and applying the coarse mesh displacements at the boundaries of the local fine mesh later [9]. In this way the fine mesh FEM calculations are performed in a second step with the load cases defined by the prescribed displacements from the coarse mesh and by the local pressures and inertia of the fine mesh. The above procedure should be performed for each operating condition, defined by loading condition, wave frequency and heading, and for both real and imaginary part of the loading, resulting in the RAOs of the stresses in each particular structural detail, Figure 2.

It should be noted that special care should be given to the separation of the quasi-static and dynamic parts of the response to ensure a proper convergence of the results. The quasi-static part of the response is calculated using the so called quasi-static method as described in [3], and dynamic part of the response is calculated by summing up the dynamic contribution of each mode.

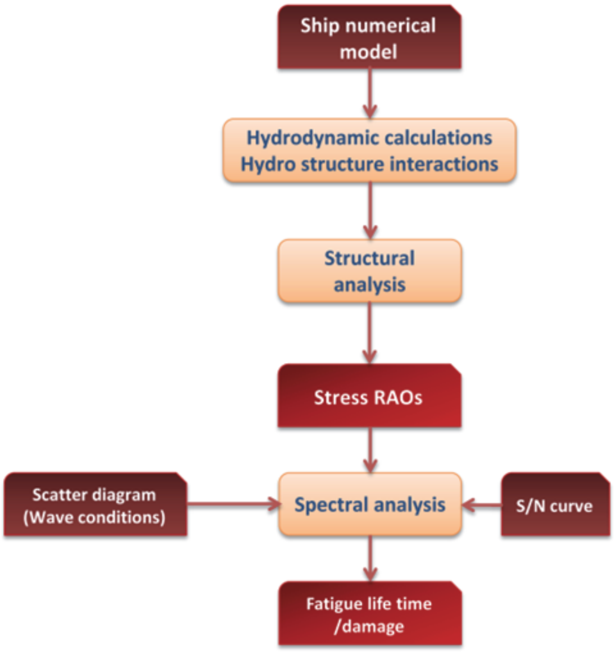


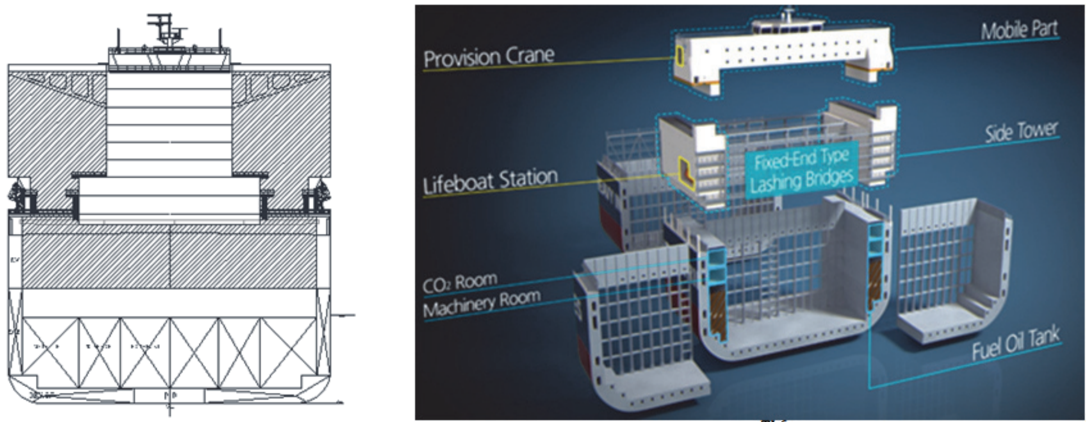
Figure 3. Fatigue assessment flowchart.

After transfer functions of stresses are obtained, spectral analysis is performed and based on the selected S/N curve and wave scatter diagram, fatigue life/damage is calculated.

3. Ship particulars, calculation models and setup

ULCCs having capacity over 10,000 TEU normally adopt the 2-island type superstructure in which a deckhouse structure for accommodation is located in the ship's mid body and separated from the other funnel and engine casing structure [10],[11]. Figure 4a shows an arrangement of compartments and spaces around accommodation in traditional design. The shaded areas within the range between upper deck and bridge wings are unused spaces and available for extra loading. The space under upper deck except parts for fuel oil tankers and operation of machineries and facilities are also available for additional loading.

A new HHI SkyBench™ 19000 TEU ULCS is considered, with main particulars given in Table 1. The idea of SkyBench™ starts from those unused space adopting mobile concept. Figure 4b shows an arrangement of compartments in SkyBench™. It is a HHI's patented concept with particular aim to extend cargo capacity and also potentially having some safety benefits, Figure 5. The bench-shaped structure located in the uppermost position indicates a mobile part of accommodation. The two structures located in both sides to support the mobile part have been named as side tower. Side towers share the function of accommodation together with mobile part. To arrange a cargo space for one more 40ft-bay inside hull structure, fuel oil tanks which are located under accommodation with the size of about 40ft in length are rearranged with two parts. Each of the tanks has two 40ft-bays in length and higher height compared to the traditional design for ensuring the equivalent tank volume. This concept features a bridge and three upper decks mounted on rails and able to move longitudinally. By using the void beneath the sliding block for additional storage, as well as resizing and repositioning fuel tanks, room is created for an additional two 20ft container bays. The SkyBench™ mechanism takes ten minutes to operate, using four electric drive train units to move the block. The two 40ft side casings on which the accommodation block rests provide structural strength and hold lifeboats, provision cranes and utility rooms. In an emergency, the sliding block is detachable and is designed to float independently of the vessel. Finally, this concept gives extended capacity loading around 270, 350 and 450 TEU in 11,000, 14,000 and 19,000 TEU class container carriers compared with the traditional, respectively.



a) Conventional design　　　b) SkBench™ design

Figure 4. Arrangement of compartments in way of accommodation in traditional and SkyBench container carrier.

Table 1. Main particulars of a HHI SkyBench™ 19000 TEU container ship

Length over all, L_{OA} [m]	400
Length between perpendiculars, L_{PP} [m]	383
Breadth, B [m]	58.6
Depth, H [m]	30.5
Design draught, T_d [m]	14.5
Scantling draught, T_s [m]	16.0
Displacement at full load, Δ_F [t]	212913
Service speed, v_s [kn]	23.0

Figure 5. HHI SkyBench^{TM} concept [12].

Global FE model of the considered ship, having 110896 elements and 31408 nodes, with indicated position for fatigue life assessment, is presented in Figure 6. In total 18 positions of interest are defined and corresponding fine mesh models of selected structural details are shown in Figure 7.

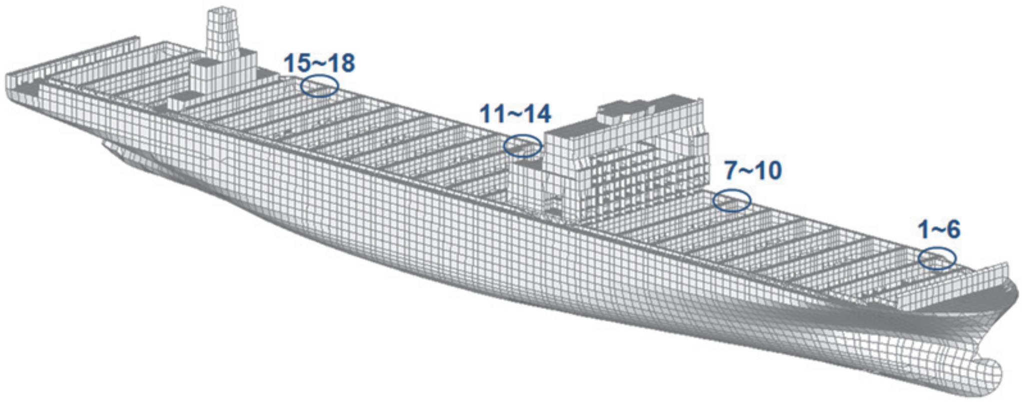
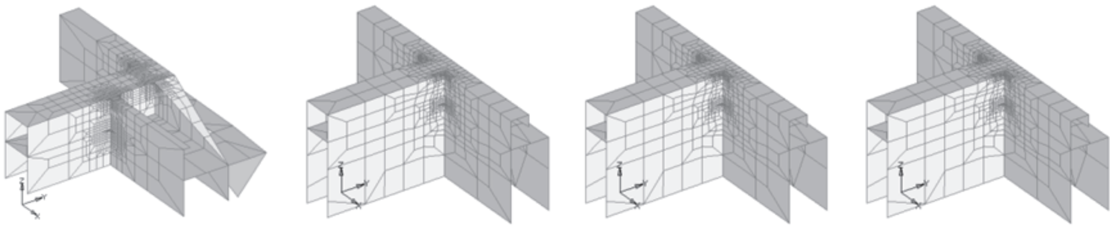


Figure 6. FE model of a HHI SkyBench^{TM} 19000 TEU container ship with indicated positions for stress concentration (fatigue life) assessment.



1~6 7~10 11~14 15~18

Figure 7. Fine mesh FE models of selected structural details.

Beside both FE global and local models of a ship structure, applied procedure also requires generation of the so called integration mesh and hydrodynamic mesh, respectively, Figure 8. The former is extracted directly from the structural model, and then the latter one, having 5984 elements on hull, is generated automatically using the existing software routines and slightly adapted for the sake of smooth computations.

The loading and operating conditions, i.e. calculation setup are established according to [3]. A single loading condition giving maximum still water bending moment in hogging is considered and worldwide scatter diagram is used. The sea states are modeled by a Pierson-Moskowitz spectrum and "cos n" spreading function, with n=2. The ship speed is taken to be as 60% of the ship design speed in all sea states, while wave headings are considered uniformly distributed from 0° to 350° with step of 10.0°.

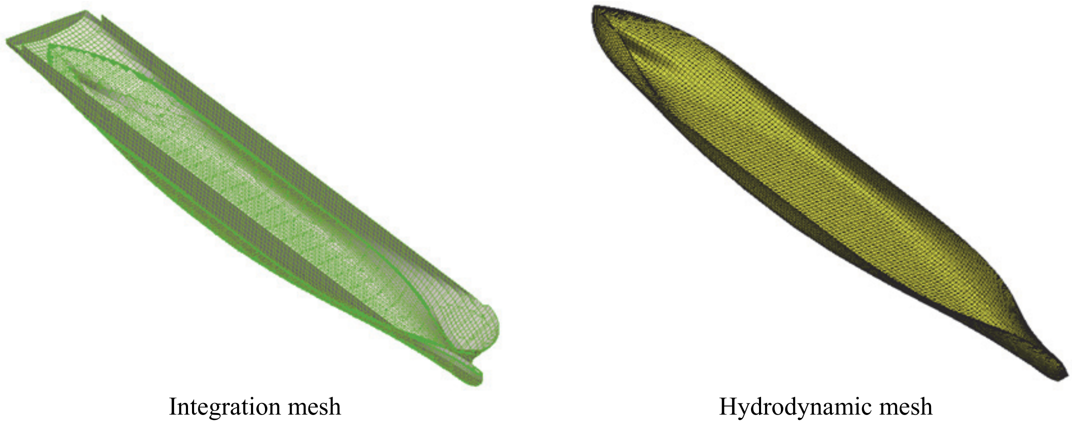


Figure 8. Integration and hydrodynamic meshes.

4. Results

In this section, results of still water load case and ship response in waves are presented, respectively. First, modal analysis of the considered ship is performed, whereas 10 elastic modes are retained for hydroelastic computations. For illustration first 6 elastic modes and corresponding dry natural frequencies are shown in Figure 9.

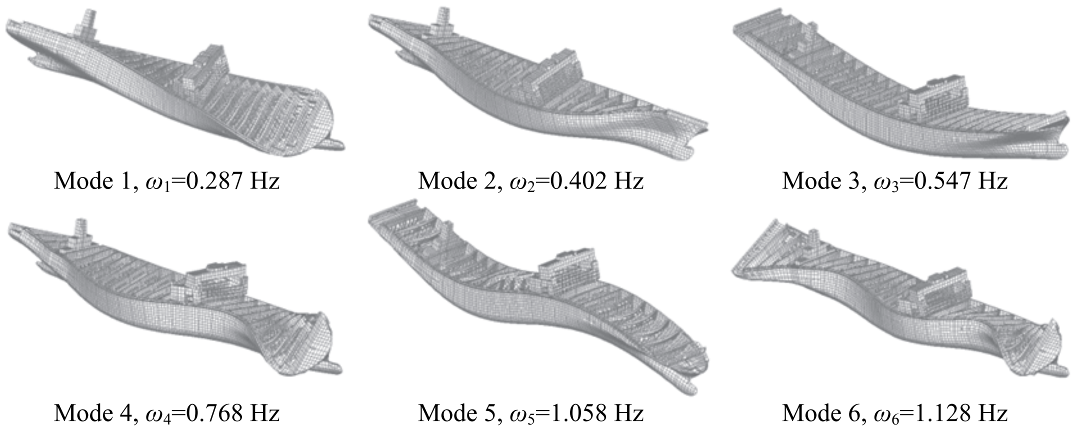


Figure 9. Mode shapes and natural frequencies a HHI SkyBench^{TM} 19000 TEU container ship.

4.1. Still water load case

In Figure 10, still water bending moment and shear force from loading manual are compared to those obtained by the used software, and values are in very good agreement. Still water case results are actually very useful as recommended checks of structural and hydrodynamic model consistency, their relative positions in global coordinate system, mass modelling within the structural model and basic calculation setup, respectively.

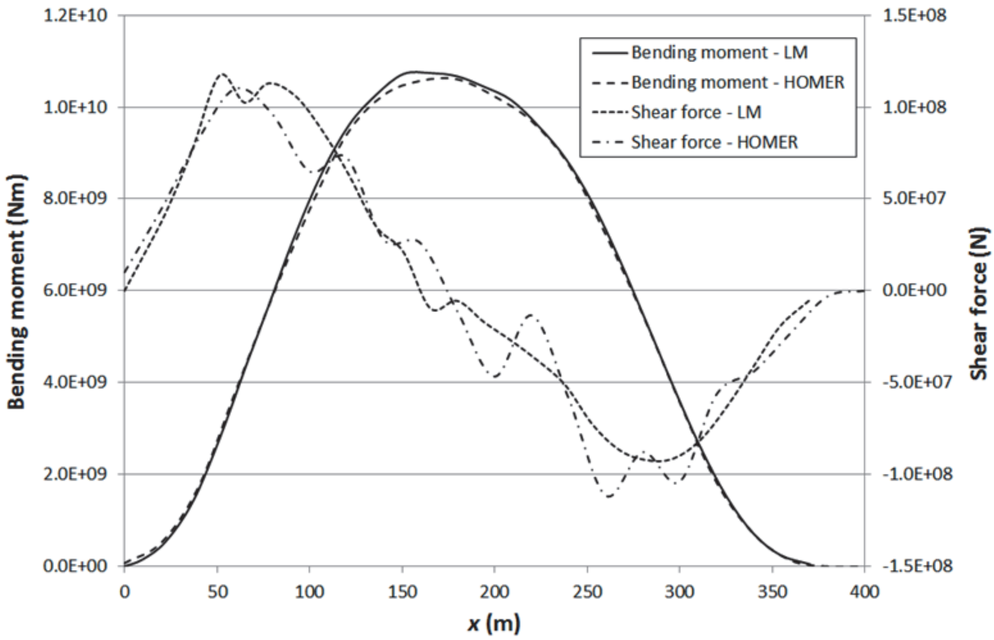


Figure 10. Still water bending moments and shear forces of a HHI SkyBench^{TM} 19000 TEU container ship.

In that sense it is useful to verify hydrostatic pressures on ship hull, Figure 11, position of structural model relative to free surface, Figure 12, or positions of fine mesh models used in top-down procedure relative to ship structure within natural mode shapes, as shown in Figure 13. Still water deflections and von Mises stresses are presented in Figures 14 and 15, respectively, and obtained values are at expected levels.

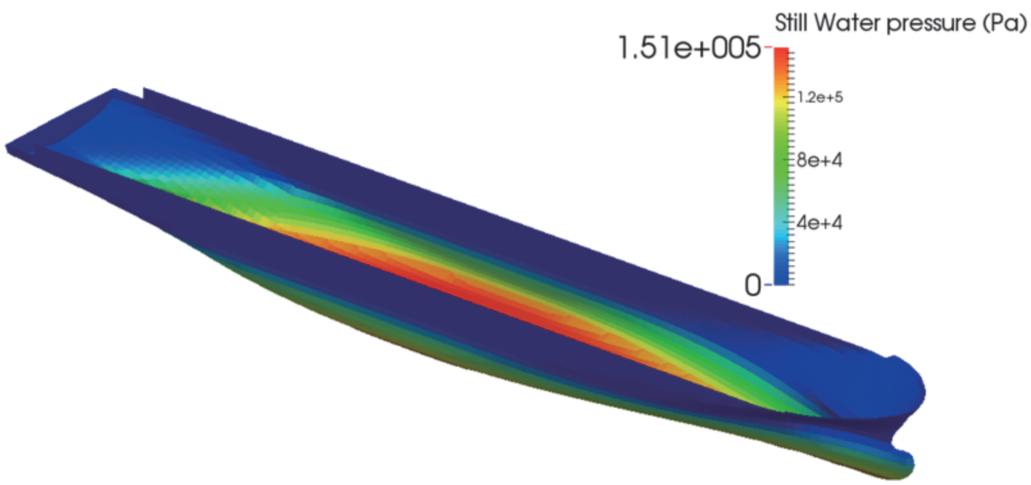


Figure 11. Hydrostatic pressures on ship hull.

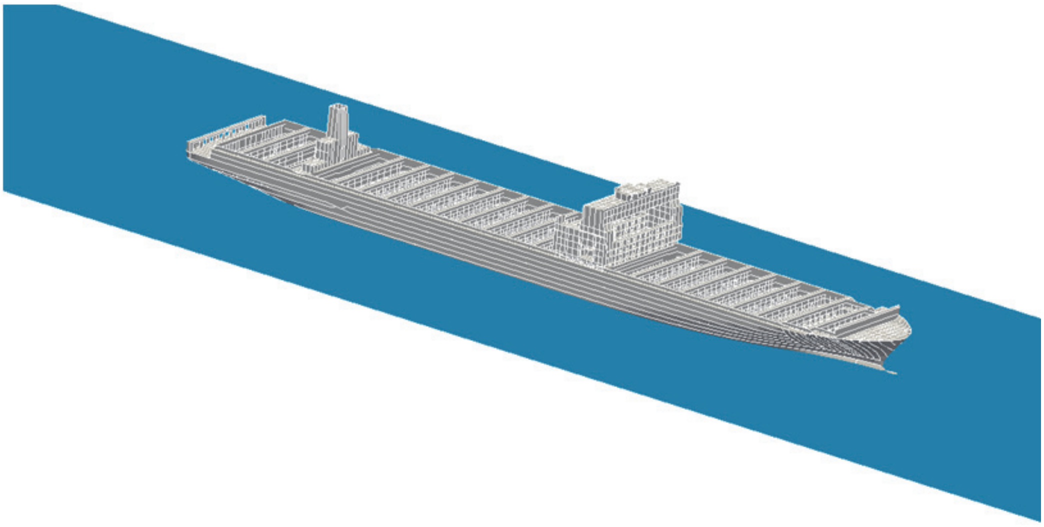
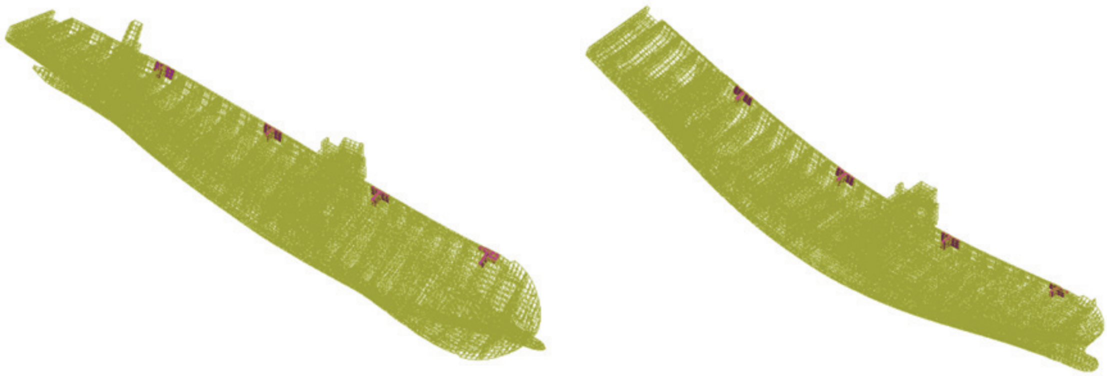


Figure 12. Position of structural model relative to free surface.



Mode 1 Mode 3

Figure 13. Position of fine meshes relative to structural mode within selected modal deformations.

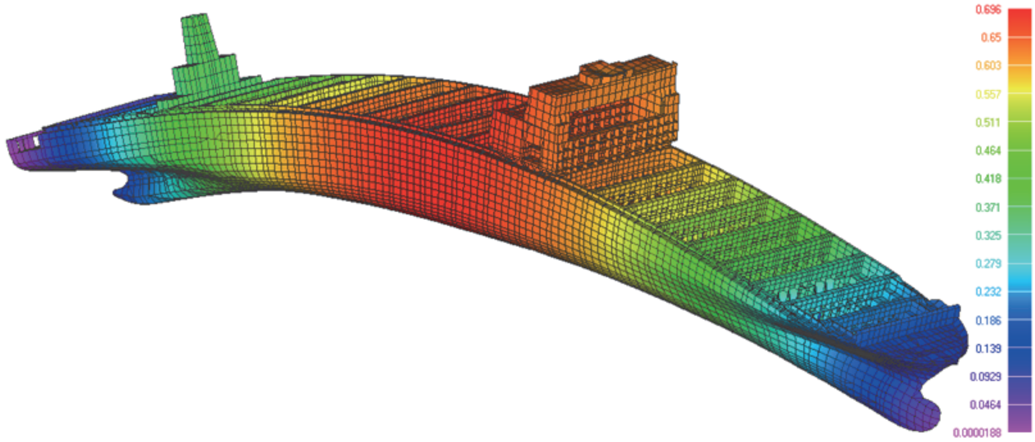


Figure 14. Still water deflection.

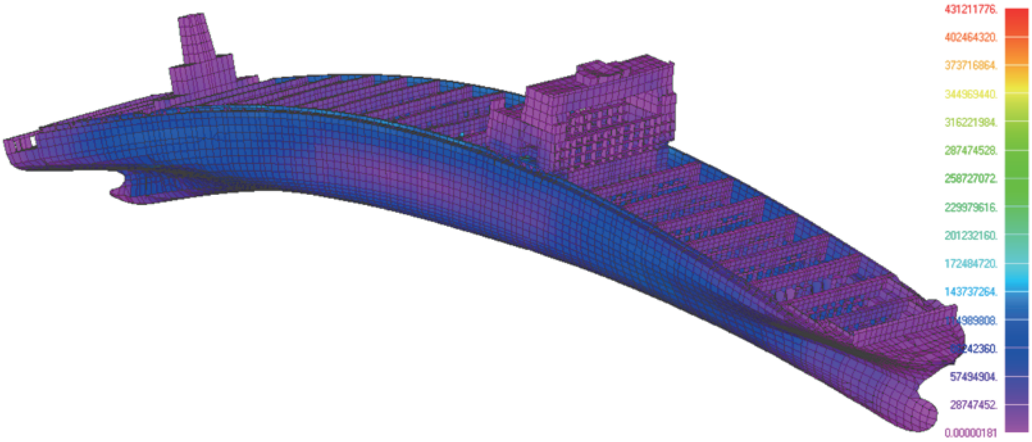


Figure 15. Still water von Mises stresses (Pa).

For illustration, still water von Mises stresses in structural details 1~6 is shown in Figure 16.

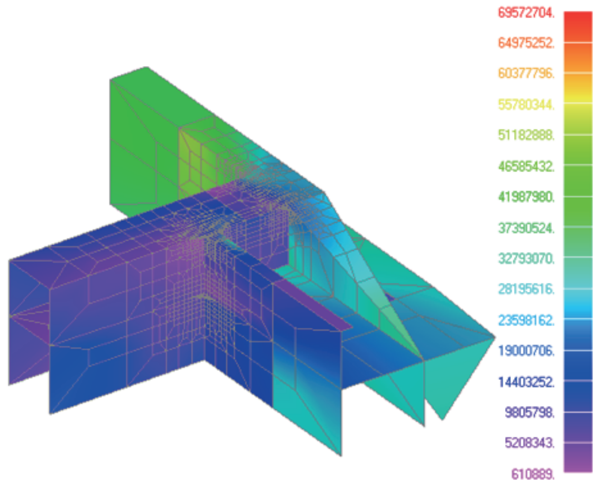


Figure 16. Still water Von Mises stresses in details 1~6 (Pa).

4.2. Ship response in waves – fatigue life of selected structural details

Global response of a ship is represented with RAOs of vertical bending moments and horizontal bending moments at midship for β=180° and 130°, respectively, Figures 17 and 18, where total response is decomposed into the quasi-static and dynamic component. Also, RAOs of torsional moments at 0.25L and 0.75L are shown in Figures 19 and 20.

Similarly as sectional moments, obtained stresses for fatigue computation are also decomposed into rigid body component and elastic contribution. Due to brevity, here only total stress RAOs of a selected structural detail are shown as a sample, Figure 21.

Stress RAOs are used as input data for fatigue computation. As the representative one, the axial stress in rod elements at the hatch corner radius free edges of fine mesh FE models is used. Sailing factor is assumed to be 0.85 and mean stress effect is included in the calculation.

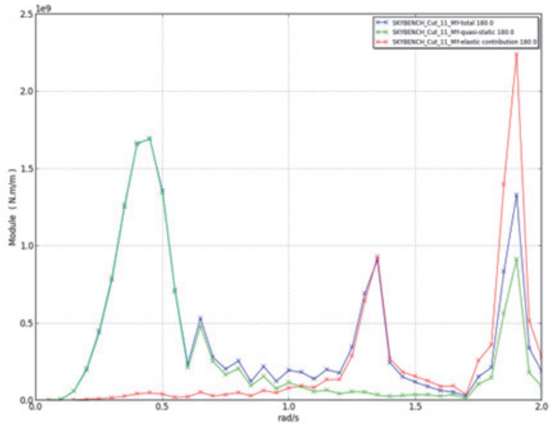


Figure 17. RAOs of vertical bending moment at midship, β=180°.

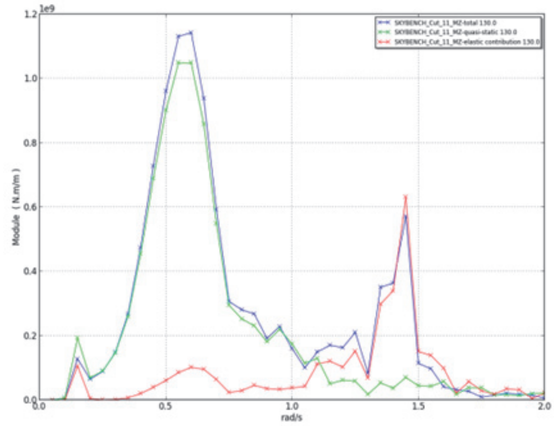


Figure 18. RAOs of horizontal bending moment at midship, β=130°.

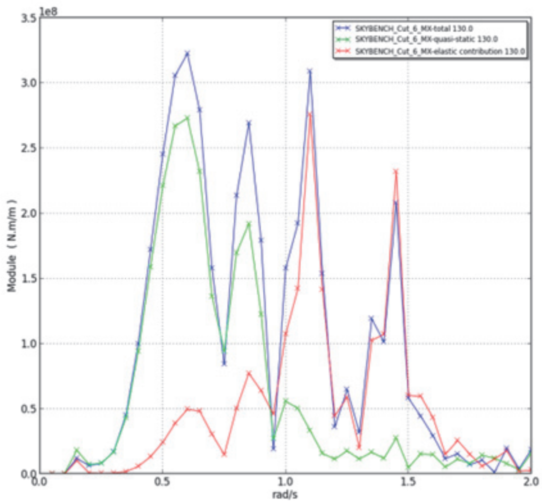


Figure 19. RAOs of torsional moment at 0.25L, β=130°.

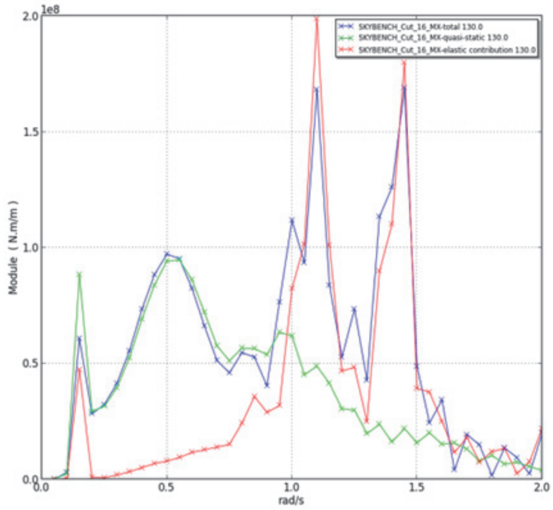


Figure 20. RAOs of torsional moment at 0.75L, β=130°.

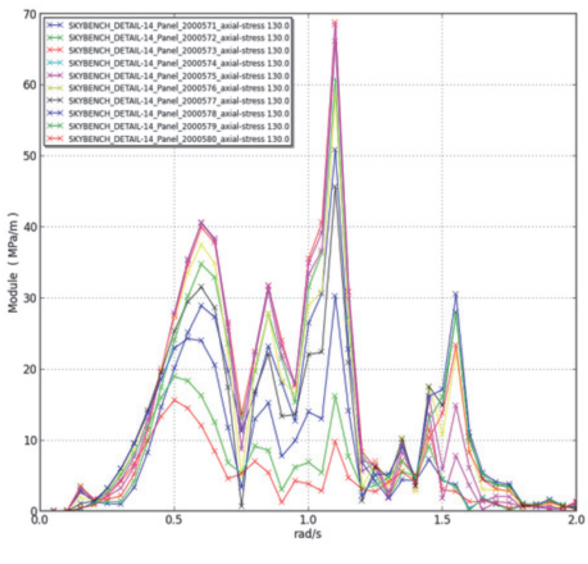


Figure 21. Example of total stress RAOs for β=130°, Detail 14.

Fatigue life of selected structural details is presented in Table 2. As expected, the lowest values are obtained for hatch corners in the vicinity of engine room area, which are typical critical details for container ships from the viewpoint of fatigue.

Table 2. Calculated fatigue life values of selected structural details

Position	Fatigue life (years)		Position	Fatigue life (years)	
	Quasi-static	Total		Quasi-static	Total
1	21689411	3320706	10	523.9	77.74
2	595424	115384	11	73.76	55.87
3	16642353	11328706	12	88.63	65.25
4	2073	439.6	13	93.46	31.18
5	328835	45035	14	125.2	39.35
6	1072	232.6	15	17.16	6.90
7	288.1	158.8	16	536.2	236.1
8	2376	236.1	17	8.66	3.42
9	288.1	158.8	18	813.9	247.4

Beside improvements of strengthening of the above mentioned structural details with slightly lower fatigue performance of the ship which is being designed at the moment, future calculations will be extended to structural details of the SkyBench^{TM} superstructure area, bearing in mind pronounced geometrical discontinuities.

5. Concluding remarks & future work

Preliminary results of hydroelastic analysis of new HHI SkyBench^{TM} container ship design, related to fatigue assessment of several structural details, are presented in the paper. The analysis was performed by general hydro-structure tool HOMER, combining 3D FEM model for the structure and 3D potential flow code for fluid modelling. Modal approach is employed for the determination of global ship hydroelastic response, and top-down procedure is applied to determine stress concentrations using the fine mesh models of selected structural details.

Further investigations will be oriented to the assessment of whipping contribution to the accumulated fatigue life of ship structural details and analyses of ship extreme responses, whereas the list of the analyzed details will be extended to those in the front superstructure area. Also, comparative analysis will be performed in order to assess potential differences in ship hydroelastic response between new HHI SkyBench^{TM} CS design and conventional container carrier design.

Acknowledgments

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